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RESEARCH MEMORANDUM

SOME FACTORS AFFECTING AUTOMATIC CONTROL OF AIRPLANES

By Charles W. Mathews

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RESEARCH MEMORANDUM

SOME FACTORS AFFECTING AUTOMATIC CONTROL OF AIRPLANES

By Charles W. Mathews

In aeronautics autopilots are receiving widespread attention because the human pilot is becoming inadequate as a controller for certain flight operations. As is well-known the airplane-autopilot combination is a closed system, the operation of which depends on the characteristics of both airplane and autopilot. In one widely used method of analysis of such coupled systems, the dynamics of the airplane and the autopilot are individually defined by operational expressions known as transfer functions. Although factors other than automatic control usually dictate the character of the airplane transfer functions, these transfer functions must be known in order to afford the autopilot designer a basis for determining the requirements of the autopilot.

At the outset of this discussion, the determination of airplane transfer functions from measured responses to control transients are discussed briefly in order to provide a background for subsequent discussion of factors affecting the airplane transfer functions and some implications of these factors with respect to autopilot design. Initial discussion is concerned with longitudinal control while the latter part is concerned with lateral and directional control. Although it is recognized that there are a number of airplane transfer functions of importance in autopilot design, for the purpose of illustration of the longitudinal case, the transfer function relating pitching velocity to elevator deflection is used.

Many of the available methods for deriving transfer functions from transient data in no way stipulate the type of control input to be used. Transfer functions obtained from the pitching-velocity response of the F9F airplane to various types of elevator inputs through use of the method of Donegan and Pearson (reference 1) are presented in figure 1 for the flight conditions of Mach number 0.6 and 10,000-foot altitude. The differences between results for the various types of inputs are small throughout the range of frequencies shown. A frequency response obtained directly from sinusoidal control inputs is also presented. The oscillations were induced manually by the pilot, and although the wave form was not perfect, a fairing was adequately defined which agrees well with the results from the transients. It appears, therefore, that for the range of frequencies presented, a sine-wave generator is not needed to use the forced-oscillation technique. The exact character of the very low frequency portion of the transfer function is usually not established from the flight data unless the test is specifically set up to examine the phugoid mode. The phugoid mode produces a sharp peak almost at zero frequency, and the amplitude then abruptly decreases to

zero at zero frequency. The phugoid motion is important in the regulator type of autopilot, but it generally is not of any great importance from the standpoint of command response characteristics.

Insight as to the importance of the differences between the frequency-response curves obtained from the transient inputs may be gained by reference to figure 2 which presents predicted airplane responses in pitching velocity to the elevator input shown. These responses were predicted from the various transfer-function curves presented in figure 1. The designations of the corresponding curves in the two figures are the same. The differences in the transient responses are negligible for practical purposes. A comparison of several methods (references 1 and 2) of determining transfer functions from transient flight data is presented in figure 3, and the results are shown to be in good agreement. Experience has shown that the repeatability of a given test also is good.

Having examined the ability to determine a longitudinal transfer function, the effects of altitude and Mach number on this transfer function are now illustrated and discussed. The effect of an altitude change from 10,000 feet to 30,000 feet on the F9F transfer function is shown in figure 4. Both the low- and the high-frequency responses are sharply reduced at the higher altitude. The larger ratio of peak amplitude to the static value is indicative of reduced damping while the lower frequency at the peak reflects a reduction in the natural frequency of the airplane. These effects qualitatively agree with those to be expected from theoretical considerations and are discussed in relation to automatic control subsequent to the presentation of Mach number effects.

Mach number effects on the pitching-velocity transfer functions are shown in figure 5 for the F-86 airplane (reference 3) which was chosen because it affords flight data in the transonic range. At subsonic speeds where no large changes in the longitudinal-stability derivatives occur, the expected effect of increase in Mach number would be simply to stretch the frequency-response curves in the direction of the frequency axes reflecting an increase in natural frequency of the airplane proportional to the Mach number increase. This expectancy is borne out by the F-86 data in that the low frequency and peak value of amplitude ratio are not appreciably changed by the increase in Mach number, while the frequencies at which the peak occurs and at which the phase curves cross zero gradually increase resulting in improvement in the high-frequency amplitude and phase response. As the transonic range is entered, the general decrease in scale of the amplitude ratio is indicative of a decrease in the effectiveness of the elevator, while the more rapid outward shift of the peak amplitude ratio and phase curves and the large decrease in amplitude ratio at low frequencies is indicative

of a large increase in the static stability of the airplane; at the higher Mach numbers the comparatively large ratio of peak amplitude to the low-frequency value and large leading phase angles denote an appreciable loss in damping.

The effect of the variations in transfer function produced by the changes in Mach number and altitude just discussed on the requirements of a pitch-attitude autopilot are examined briefly in figure 6. The measured response characteristics of an actual autopilot were used. Pitch rate feedback was incorporated in order to obtain a good command response.

The upper time history in figure 6 shows the response of the airplane-autopilot combination to approximately a step command in attitude at a Mach number of 0.7 and an altitude of 35,000 feet when the various gains in the system were adjusted to provide the lowest response time. With this adjustment the autopilot gains were very high, producing about 20° of elevator deflection for 1° of attitude error. In the practical situation these gains might very well be limited by other considerations such as servo power, loads, saturation, or the possibility of exciting high-frequency chatter. Based on the limited considerations involved in the analysis, however, it was possible to obtain a very rapid response with a good degree of stability. The autopilot gains, of course, could be relaxed at the expense of the response if it were established that a poorer response could be tolerated.

The effect of holding the autopilot gain settings constant and changing the flight condition is shown by the time histories in the middle of figure 6. With altitude reduction the system becomes violently unstable while with the increase in Mach number the degree of stability is very low. As shown by the time histories in the lower part of figure 6, a response on a par with that for the original condition may be obtained for the other cases by gain adjustments.

At Mach numbers near or slightly above unity, it was not possible to obtain as good a low-frequency response for the airplane-autopilot combination by gain adjustment, and as a result, the command response was more sluggish.

Data from full-scale flight tests for determination of transfer functions are not available in the supersonic-speed range. Such data have been obtained using the rocket-model technique. In order to scale up the mass characteristics and alter the operating altitude, however, it is necessary first to reduce the data to stability derivatives and then recompute the transfer function. Such computations have been made for three different configurations having widely differing mass characteristics. Results for a delta-wing configuration are presented in figure 7, and results for an unswept-wing configuration and a swept-wing

configuration are presented in figures 8 and 9. Possible differences between the model and full-scale data due to elastic effects were not considered. The results presented in figure 7 for a Mach number of unity and below were computed at an altitude of 40,000 feet, and the results for the supersonic Mach numbers were computed at an altitude of 60,000 feet.

The alteration of the transfer function of the delta-wing configuration between $M = 0.8$ and $M = 0.9$ is typical of the subsonic effects previously described for the F-86. The change occurring between $M = 0.9$ and $M = 1.0$ is indicative of an appreciable increase in static stability. In going to a Mach number of 1.2 at 60,000 feet, the alterations in the transfer function do not indicate any appreciable change in stability derivatives but result primarily from the altitude change. The small differences between the transfer functions for $M = 1.2$ and $M = 1.7$ are surprising considering the large Mach number change involved. This result would indicate a general reduction in the values of all of the stability derivatives between these two Mach numbers.

Comparison of results for the delta-wing configuration and the other two configurations shows that there are pronounced differences in the trends of the transfer functions of the three, and different handling would be required in each case such as different programming of the autopilot gains. Some important characteristics of the transfer functions, however, are common to all three configurations. These characteristics are the very poor low-frequency response and the very large peak magnification. The most predominant factor in producing these characteristics is the basic one of high-altitude operation, but generally the effect of Mach number in increasing the static stability and reducing the control effectiveness and damping serves to increase these trends.

Turning now to the lateral-transfer functions of airplanes, some features of these transfer functions will be discussed in relation to the analysis of airplane-autopilot combinations. First, let us examine the character of a transfer function of the F9F airplane (fig. 10) relating rolling velocity to aileron deflection. Neglecting the sharp peak, the amplitude-ratio and phase-angle variations appear to be those for a viscous or first-order lag which is to be expected since the airplane has no static stability in roll. The presence of the spike, of course, is indicative of the existence of a lightly damped Dutch roll oscillation, and this mode is present in the rolling transfer function because of the strong coupling between the rolling, yawing, and sideslipping motions of the airplane.

The remarks made previously relative to the phugoid motion in the longitudinal case generally apply also to the spiral mode which exists in the lateral case. When the spiral mode is included, the amplitude

response is zero at zero frequency but increases almost immediately to the value shown.

The importance of the Dutch roll mode on the response in rolling velocity to a unit step in aileron deflection is shown in figure 11. Although the oscillation is poorly damped it is not excited greatly by aileron deflection.

The foregoing characteristics of the F9F airplane suggest the possibility of simplifying lateral transfer functions under some conditions. This possibility may be examined through use of the analytical expression for the transfer function which relates rolling velocity to aileron deflection ($\dot{\phi}/\delta_a$). This expression is presented in figure 12 in terms of the imaginary frequency variable $j\omega$. The quadratic factor in the denominator which defines the period and damping of the Dutch roll mode may be found in some instances to be almost the same as the quadratic factor in the numerator, and the linear factor representing the spiral mode as implied previously is important only at very low frequencies. In view of these characteristics on some occasions it may be adequate to approximate the rolling-velocity transfer functions by an equivalent single-degree-of-freedom system defined by the expression $K_1 \frac{1}{j\omega + D}$.

Because of the coupling which exists between the rolling and yawing motions of the airplane, it is necessary to consider the effect on the roll transfer function of an automatic control loop in the yaw channel. Calculations indicate that systems of the yaw-damper type which apply yawing moments proportional to yawing velocity and systems of the regulator type which apply yawing moments proportional to sideslip or lateral acceleration would strengthen the possibilities for use of the approximation provided the natural frequency of the autopilot is high.

A point worth noting is that it may be advisable to eliminate the possibility of using a simplified form of the transfer function in order to take advantage of certain coupling effects. For example, calculations have shown that an automatic control which effectively applies a yawing moment proportional to rolling velocity improves the damping of the Dutch roll oscillation and improves the rolling response to an aileron deflection.

The transfer function relating yawing velocity to rudder deflection ($\dot{\psi}/\delta_r$) sometimes affords a similar possibility for simplification. The quadratic factor in the numerator in many instances agrees closely with a quadratic factor which defines the spiral and rolling modes (see fig. 12). The constant term of the linear factor in the numerator is

usually small so that in many cases the transfer function may be simplified to the equivalent single-degree-of-freedom system presented in figure 12. The linear factor in the roll approximation and the quadratic factor in the yaw approximation are the actual factors of the stability quartic and as such may contain coupling effects. Because of this coupling these factors may differ considerably from those obtained by simply considering the airplane to have a single degree of freedom in either roll or yaw.

The presence of an automatic control system in the roll channel may alter the quadratic representing the equivalent single degree of freedom in yaw. Calculations have shown that, for a typical but hypothetical airplane operating at high altitude, the existence of an unstable Dutch roll oscillation which doubled amplitude in 7 seconds was stabilized to the extent of halving amplitude in 5 seconds by incorporation of a roll-attitude system with a gearing of 0.2 between aileron deflection and bank-angle error (reference 4). In establishing the coefficients for the equivalent single-degree-of-freedom approximation in yaw, it is possible that the roll autopilot could be considered perfect and its effect included in the form of another stability derivative.

In addition to the lateral transfer functions just discussed, there exist cross transfer functions. Possibilities for simplification of these transfer functions have not been investigated. The amplitude ratio of yawing velocity to aileron deflection is usually small compared to other lateral transfer functions; however, the amplitude ratio of rolling velocity to rudder deflection is usually large. In fact the amplitude in roll of the Dutch roll oscillation induced by rudder deflection is normally greater than the amplitude in yaw and in some cases has been calculated to be roughly five times as large. In the presence of tight roll stabilization the importance of rolling due to rudder deflection should be diminished, however.

Some results which afford a comparison between the use of the complete transfer function relating yawing velocity to rudder deflection and the simplification previously discussed are presented in figure 13. The data presented show the effect of variations in the parameters which define the transfer function of the autopilot. In the example the autopilot was used as a yaw damper and its transfer function was assumed to be a quadratic lag. The airplane was hypothetical. These results apply for a given static sensitivity of the autopilot. The damping ratio and natural frequency of the autopilot are the ordinate and abscissa, respectively, and the contours are lines of constant damping for the airplane-autopilot combination. The dashed lines are for the complete airplane transfer function while the solid lines are for the single-degree-of-freedom approximation. The difference between the results is negligible. The value of $T_{1/2}$ of 2.6 is the same as

for the airplane alone; the value of 0.73 is the same as would be obtained with an autopilot having no lag and a constant amplitude ratio at all frequencies; and the value of 0.38 is the maximum obtainable with the type of autopilot investigated. The position of the point of highest damping indicates that there is no particular reason in this example to increase the natural frequency of the autopilot much beyond a value of about 10 radians per second.

In summary, it appears that the available methods for obtaining airplane transfer functions from measured transients define the transfer function adequately for use in autopilot design. Flight results using this technique show that effects of high-altitude operation are to reduce severely the low-frequency response in pitching velocity and increase greatly the peak magnification. These effects in general appear to be aggravated by supersonic operation because of trends toward increased static stability, lower damping, and lower control effectiveness. In addition, the more or less inconsistent trends in the transfer function resulting from Mach number effects on the stability derivatives are fairly large and vary appreciably from configuration to configuration.

Examination of lateral transfer functions indicates that equivalent single-degree-of-freedom systems may be used to approximate some of these transfer functions in certain cases, but these approximations of the transfer functions are not necessarily the same as would be obtained in considering the airplane to have a single degree of freedom in yaw or roll. The possibility of using a single-degree-of-freedom approximation for the rolling case is strengthened when a yaw damper and a sideslip regulator are incorporated in the yaw channel. The presence of roll stabilization may affect the equivalent single-degree-of-freedom approximation in the yawing case. Eliminating the possibility of using single-degree-of-freedom approximations may be desirable in order to take advantage of favorable cross-coupling effects in the design of the autopilot.

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3. Triplett, William C., and Smith, G. Allan: Longitudinal Frequency-Response Characteristics of a 35° Swept-Wing Airplane As Determined from Flight Measurements, Including a Method for the Evaluation of Transfer Functions. NACA RM A51G27, 1951.

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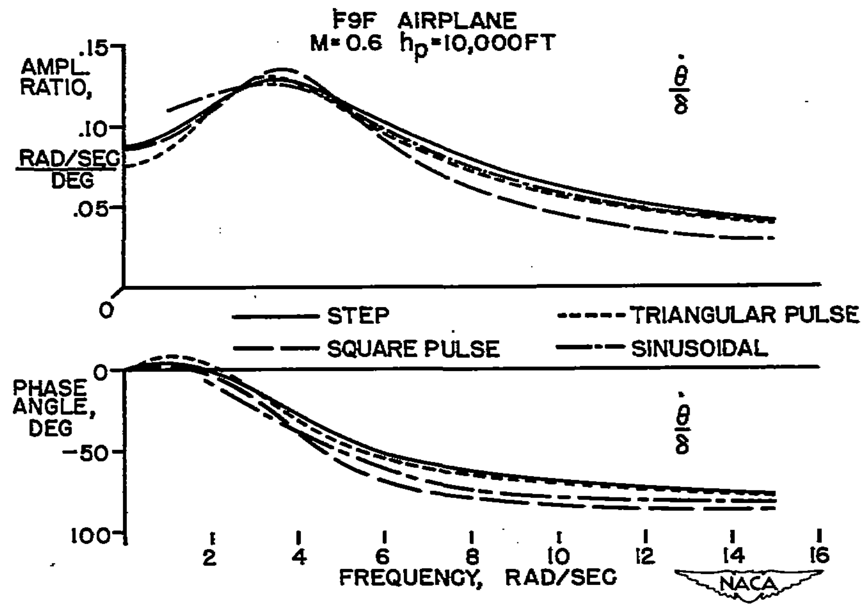

Figure 1.- Effect of type of elevator input on pitching-velocity transfer function of F9F airplane.

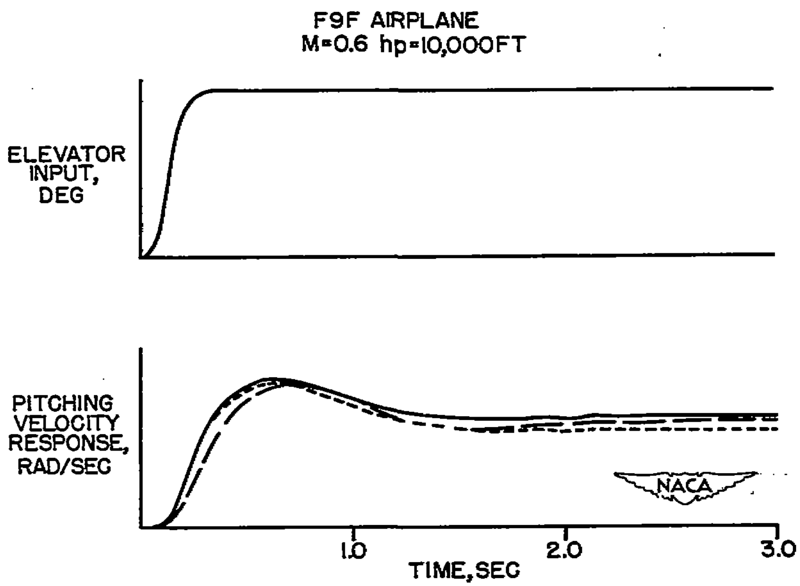

Figure 2.- Time histories of pitching-velocity response of the F9F airplane to elevator input shown as obtained from transfer functions presented in figure 1.

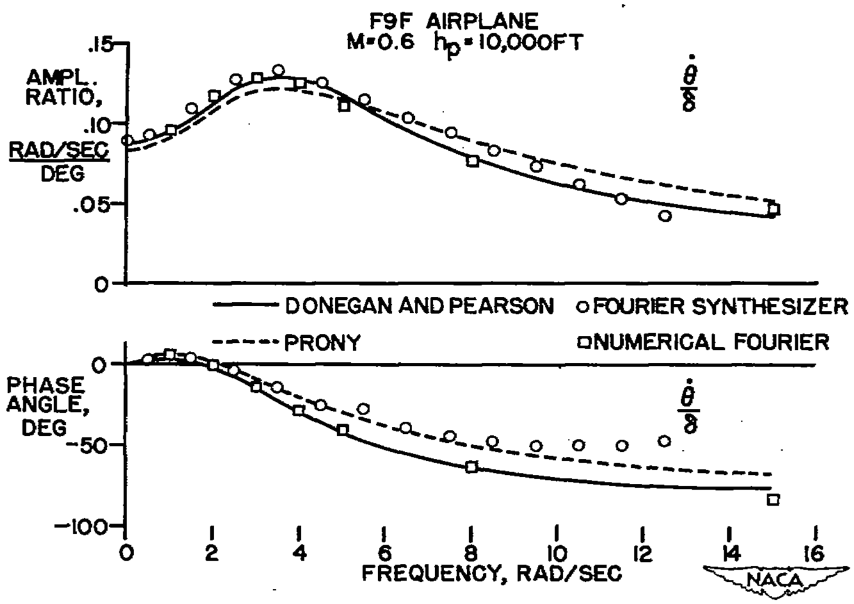

Figure 3.- Comparison of methods of obtaining a longitudinal transfer function from transient flight data.

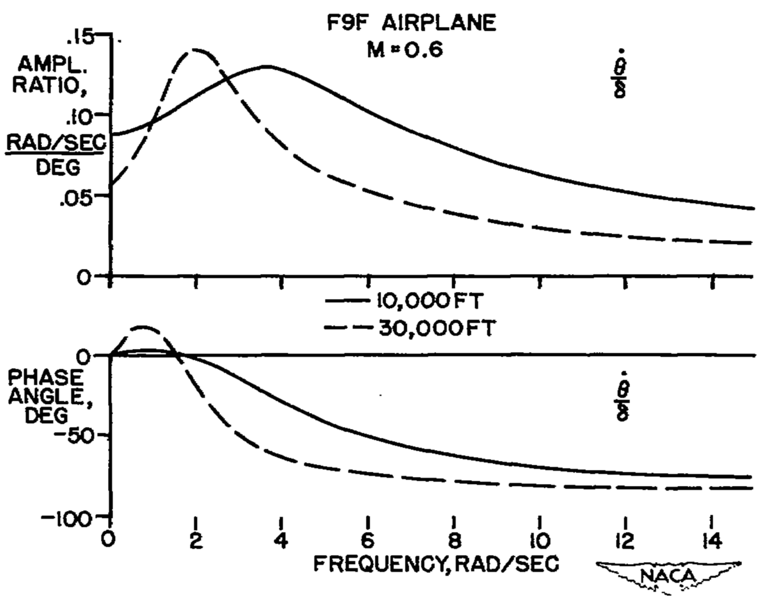

Figure 4.- Effect of altitude on pitching-velocity transfer function of F9F airplane.

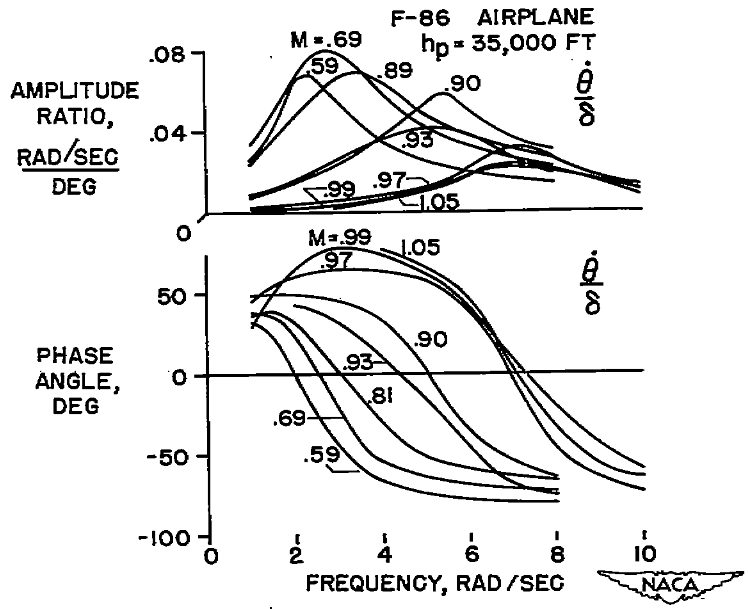

Figure 5.- Effect of Mach number on pitching-velocity transfer function of F-86 airplane.

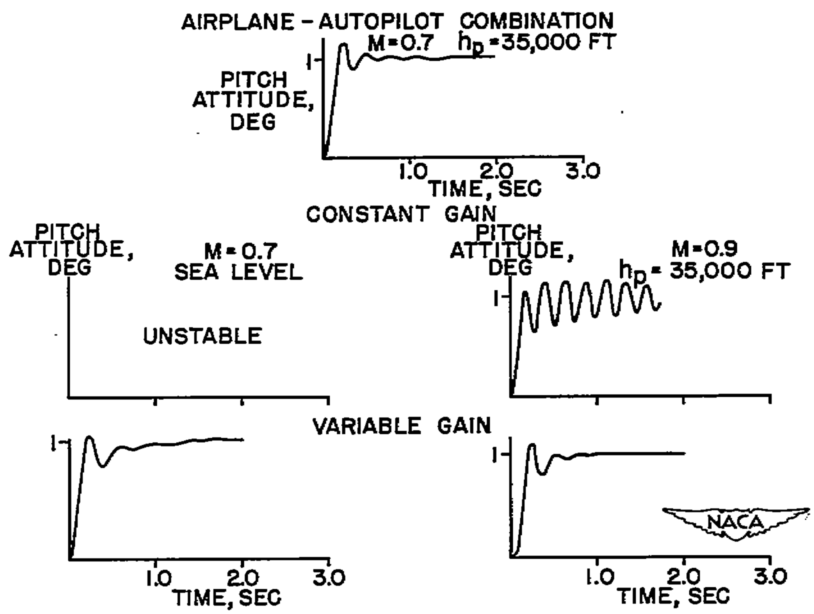

Figure 6.- Effects of altitude and Mach number on the indicial response of a swept-wing airplane - autopilot combination.

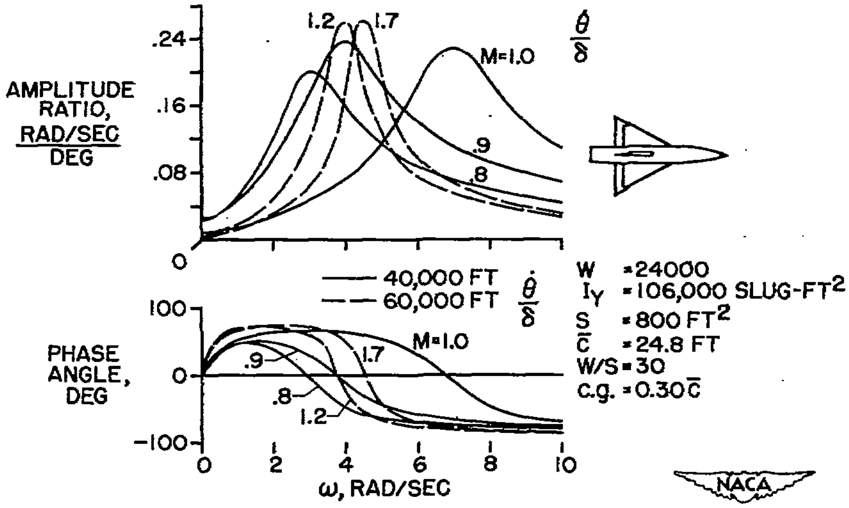

Figure 7.- Effect of Mach number on pitching-velocity transfer function of a supersonic-airplane configuration having a delta wing.

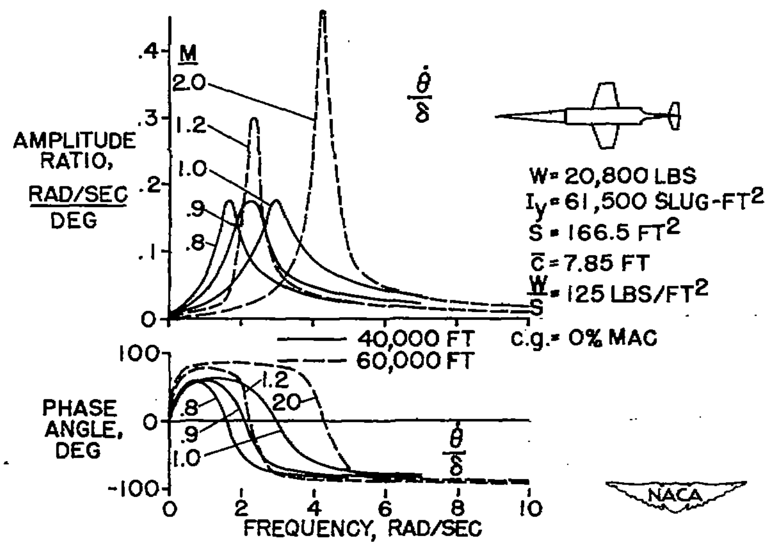

Figure 8.- Effect of Mach number on pitching-velocity transfer function of a supersonic-airplane configuration having an unswept wing.

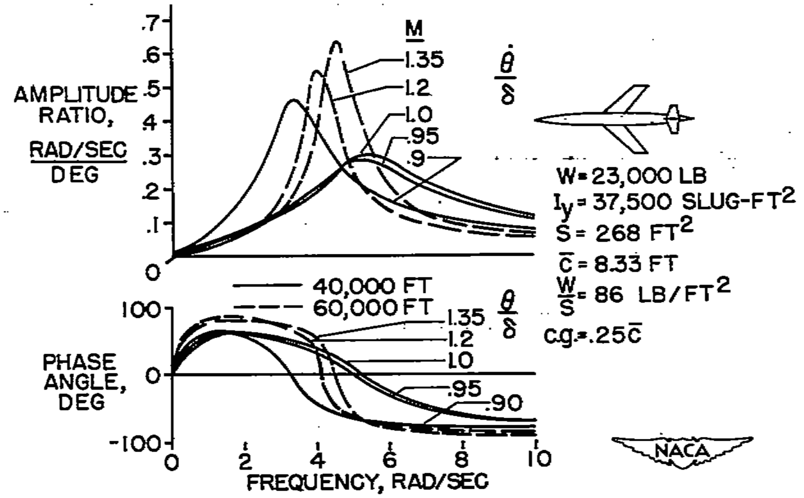

Figure 9.- Effect of Mach number on pitching-velocity transfer function of a supersonic-airplane configuration having a swept wing.

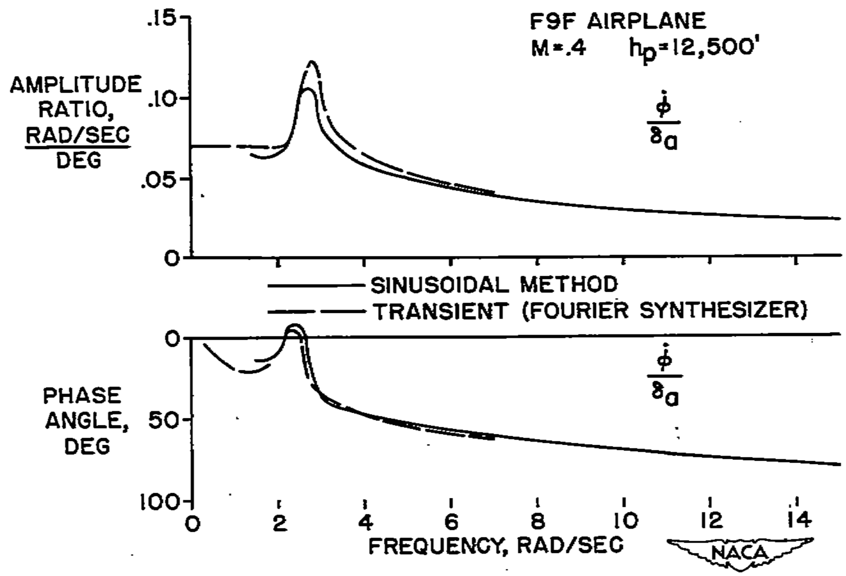

Figure 10.- Transfer function of F9F airplane relating rolling velocity to aileron deflection.

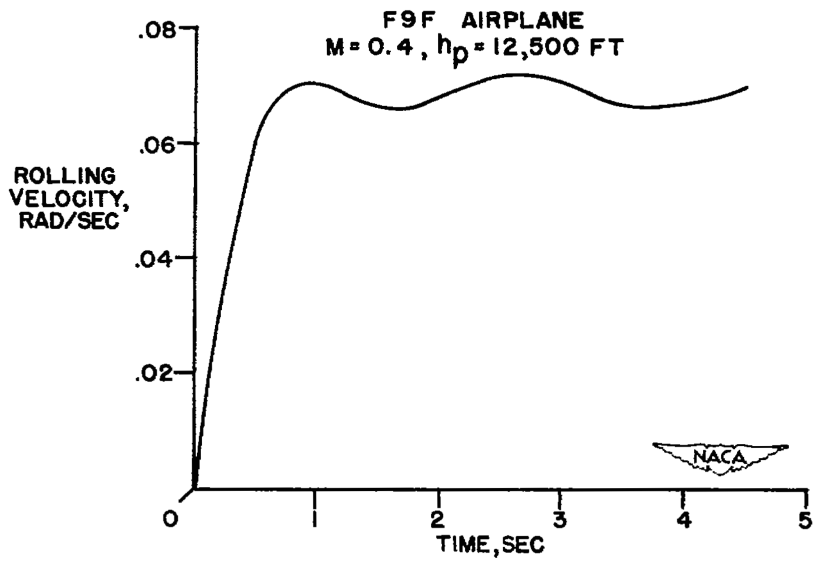

Figure 11.- Time history of rolling-velocity response of F9F airplane to a unit step in aileron deflection.

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$$\frac{\dot{\phi}}{\delta_a} = K_1 \frac{j\omega\left[(j\omega)^2 + Aj\omega + B\right]}{\underbrace{(j\omega + C)}_{\text{SPIRAL MODE}}\underbrace{(j\omega + D)}_{\text{ROLLING CONVERGENCE}}\underbrace{\left[(j\omega)^2 + (A + \varepsilon_1)j\omega + (B + \varepsilon_2)\right]}_{\text{DUTCH ROLL}}} \qquad \frac{\dot{\phi}}{\delta_a} = K_1 \frac{1}{j\omega + D}$$

$$\frac{\dot{\psi}}{\delta_r} = K_2 \frac{(j\omega + E)\left[(j\omega)^2 + Fj\omega + G\right]}{\underbrace{\left[(j\omega)^2 + (F + \varepsilon_3)j\omega + (G + \varepsilon_4)\right]}_{\text{SPIRAL MODE AND ROLLING CONVERGENCE}}\underbrace{\left[(j\omega)^2 + Hj\omega + I\right]}_{\text{DUTCH ROLL}}} \qquad \frac{\dot{\psi}}{\delta_r} = K_2 \frac{j\omega}{(j\omega)^2 + Hj\omega + I}$$

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Figure 12.- Analytical expressions for two lateral transfer functions and approximate expressions applicable under limited conditions.

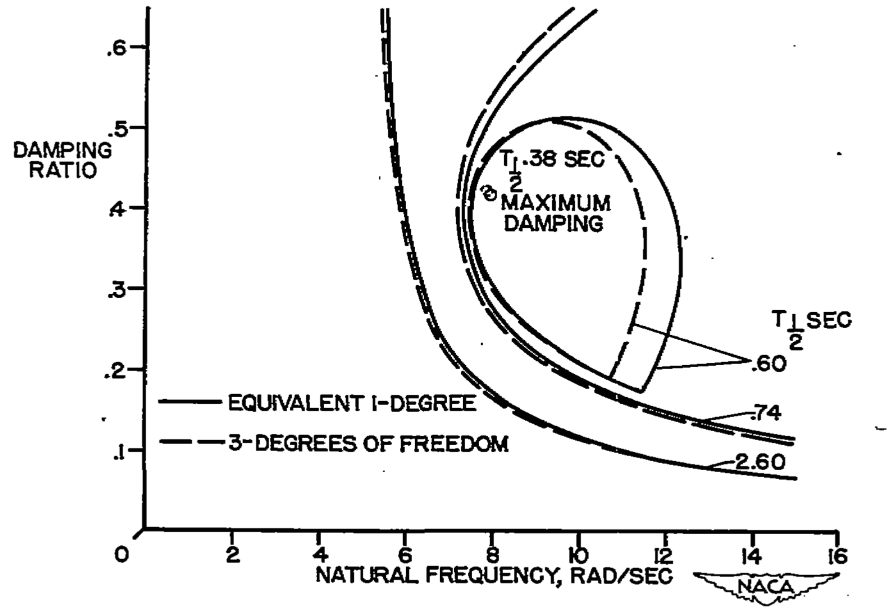

Figure 13.- The relation of the damping and natural frequency of a yaw-damper type of autopilot to the time to damp to one-half amplitude of an airplane-autopilot combination.

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